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Evaluation of a long-term potential for the development of agricultural biogas plants: A case study for the Lubelskie Province, Poland

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ABSTRACT

This article presents a review of methodologies allowing for the calculation of agricultural biogas potentials on a regional level. A definition of theoretical, technical and economic potentials as well as methods for their calculation are provided. The review of the state-of-art studies in this area has indicated that despite differences in calculation methods, procedures for approximation of theoretical and technical potentials are well established. However, there have been various approaches to elaborate a methodology to calculate the economic (market) potential. In this article a scenario building approach is applied for a case study region of the Lubelskie Province, east of Poland. The results have shown that the elaborated methodology can be applied by policy makers to integrate also other renewables in planning procedures.

Contents

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1. Introduction

Increasing oil prices and growing concerns for the national energy security and the global climate change caused by the intensive use of fossil fuels, created a potential for the locally available renewable energy sources (RES) [1,2]. In the European Union increased utilisation of green energy has become crucial for the attainment of environmental and economic goals, like the reduction of greenhouse gas emissions or energy dependency [3]. The local economic added value is created also by reversing of financial flows *i.e.* by spending money on local energy resources, which stay in the region and contribute to the increasing of regional turnover [4]. The creation of the local turnover and employment has gained increasing attention from regional policy makers [5]. However, the regional benefits (the so called regional added value) resulting from local sources are difficult to be accounted for, communicated and integrated in the regional policy documents.

Regions are expected to participate actively in the realisation of the RES goals, but very often they lack the expertise, tools and staff to enact the implementation of new, dispersed energy infrastructures. Especially agricultural areas are on one hand rich in local resources, but on the other underinvested in terms of infrastructure, organisation and intangible assets. The production of biogas is perceived as an important ingredient to provide environmental benefits for agricultural regions, such as farmers' entrepreneurship [3,6]. In the European Commission’s proposals for the future of the Cohesion Policy, the green economy is in the focal point of the 2014–2020 financing period [7], many of the measures are to be realized on a regional level. There is an indication for the *ex ante* evaluation of future investments. The methodology presented in this article can be, thus, used by regional authorities, especially in rural areas, to evaluate the potential and benefits from the development of RES (here agricultural biogas).

Many agricultural regions, including the Lubelskie Province in Poland, see their chance in supporting the development of agricultural biogas plants. The most important factors in Poland having an impact on the development of this technology are the rural structure and the profile of agricultural activities [8]. Poland is one of the countries with the largest share of agriculture land in the total area: nearly 18.9 million hectares, *i.e.* 60.4% of the total land cover. The area of Utilised Agricultural Area (UAA) in good agricultural practice amounts to *c.* 15.4 million hectares (49% of the country). In 2011, approximately 2.2 million farms operated in Poland, including 1.5 million farms of more than 1 ha. The average acreage of a farm (> 1 ha), has been slowly but steadily increasing and now it amounts to barely 9.8 ha [9].

Due to the lack of sufficient information on how to include agricultural biogas plants in the development, spatial or energy planning procedures, regional policy makers need ready to use support tools for the investigation of future regional RES options. There have been discrepancies in calculation methodologies for biomass potentials due to different scopes (theoretical, technical, economic, sustainable and implementation potentials), types of biomass analysed, objectives, system boundaries, timeframes, data inputs and methodologies [10]. The harmonisation of approaches is necessary to provide clear indications for those who will finally use them to formulate policies and future targets. Vis M. and Dees M. [11] elaborated 40 simplified methodologies for different biomass resource assessments under the BEE project; however, they indicated a need for further research leading to the increased level of detail and the standardisation of biomass potential calculation methodologies. One of the research needs indicated, was to extend the biomass potential analyses to the regional level, as most of the existing studies have had only a national focus.

This article aims at presenting a review of methodologies allowing for the calculation of agricultural biogas potentials on a regional level. Definitions of theoretical, technical and economic potentials are provided, followed by a methodology for calculation, and a case study analysis for the Lubelskie Province, east of Poland. Results are supposed to help regional policy makers to formulate targets, communicate regional added value and integrate renewables (here agricultural biogas) into regional development plans.

2. Material and methods

2.1. Definitions

Methodologies for estimation of biomass resources are split into resource focused (statistical and spatially explicit) and demand driven cost supply analyses [11]. Resource focused assessments are usually used for the evaluation of a technical potential. Spatially explicit methods are more suitable to reflect regional circumstances; however, they are more labour intensive. The scope and the level of work required to play with spatial data does not automatically translate into better quality of results [10]. It is most desirable to deal with high resolution, accurate data; however, the acquisition costs can shift preferences of planners towards less precise, estimated and low resolution data. For the purpose of regional planning it is much simpler to use the publically available, low-labour statistical data [11].

The economic (market or implementation) potential is usually expressed as demand-driven assessments [11], to reflect the penetration of biomass resources into a competitive market. Integrated assessment models are designed to assess policy questions (such as population and income growth, as well as technological developments and policy incentives), mostly by means of multi-dimensional scenario analyses. Scenario storylines can be built to reflect assumptions about projected development trends: future socio-economic, technological and environmental developments [10,12]. Angelis-Dimakis A, *et al* (2011) regional potentials for biomass projects are split into three categories [13] (Table 1) and various approaches to data availability and the assessment methods [10,13].

2.2. Theoretical potential

The theoretical potential is estimated by taking into account all biologically degradable substrates available for anaerobic digestion in a given region. It stipulates the upper value, beyond which obtaining of feedstock for biogas production is not further possible, thus, it is considered to be a good threshold value for calculation of other potentials (technical, economic and market constrained). However, the calculation of the theoretical potential for agricultural biogas has so far found no practical application due to manifold further technical, economic, legal and market constraints [14].

Table 1
Evaluation of agricultural biogas potential.

	Definition	Assessment method	Data required
Theoretical potential	The amount of the terrestrial biomass, theoretically available for bioenergy production within biophysical limits. Gross energy of the resource, primary energy contained in the supplied feedstock. In the case of residues and wastes, the theoretical potential equals total amounts produced.	Resource focused statistical or spatial explicit analyses.	Information on arable land, cultivated areas, pasture areas, livestock statistics agricultural productivity data, agricultural management systems, harvested volumes, key drivers of land use change *etc*.
Technical potential	A fraction of the theoretical potential technically available (considered are harvesting techniques, infrastructure and accessibility, processing techniques) and spatial restrictions due to competition with other land uses (e.g. food, fodder production). Ecological constraints can also be included.		
Economic potential	A fraction of the technical potential, which is economically profitable for assumed framework conditions. This potential reflects the socio-political framework such as economic, institutional and social constraints as well as policy incentives.	Demand-driven analyses • cost supply, • energy and/or economic modelling, • integrated approach.	Scenario variables

Table 2
Livestock unit coefficients.

Bovine animals	
Under 1 year old	0.400
1 but less than 2 years old	0.700
Male, 2 years old and over	1.000
Heifers, 2 years old and over	0.800
Dairy cows	1.000
Other cows, 2 years old and over	0.800
Sheep and goats	0.100
Equidae	0.800
Pigs	
Piglets having a live weight of under 20 kg	0.027
Breeding sows weighing 50 kg and over	0.500
Other pigs	0.300
Poultry	
Broilers	0.007
Laying hens	0.014
Ostriches	0.350
Other poultry	0.030
Rabbits	0.020

2.2.1. Estimation of regionally available amounts of feedstock

2.2.1.1. Animal manure. For the feedstock potential of animal manure it is suggested to make separate calculations for animal groups (cattle, pigs, poultry, sheep/goats, birds, horses, rabbits, and other livestock) [13,15]. The actual data referring to manure should be derived from the number of animals, which is justified by the structure of regional statistics: usually data referring to number of animals are grouped as per the farm size. It is recommend to multiply the livestock population by the "manure-per-animal" ratio [16].

For simplification of calculations, the number of animals should be converted into livestock units (LSU). The LSU is a reference unit, which is a grazing equivalent of one adult dairy cow producing 3000 kg of milk annually, without additional concentrated food-stuffs [17] (Table 2).

As it is not possible to perform calculation with such a detailed, labour intensive breakdown, a simplified LSU indicators is needed, in most cases, for the purpose of regional calculation aggregated "herd" LSU coefficients are used [9]:

- bovine animals: 0.8,
- equidae: 0.8,
- pigs: 0.14,
- poultry: 0.004, and
- sheep and goats: 0.1.

For bigger farms, which tend to be non-straw-bedded, the animal slurry (Q_s) can be assumed as the animal waste. For smaller farms, where straw is still used for bedding, manure (Q_m) will be the output value [9]. The theoretically available amounts of animal wastes are calculated according to the equation [18]:

$$\dot{m}_{livestock} = LSU\ Q_s(Q_m) \quad (1)$$

$\dot{m}_{livestock}$ – regionally available amounts of livestock waste per unit of time [t a^{-1}],
LSU – livestock equivalent for a given animal "herd" category,
Q_s – amount of slurry generated by LSU, 20 [t LSU^{-1}] assumed, or
Q_m – amount of manure generated by LSU, 10 [t LSU^{-1}] assumed.

2.2.1.2. Energy crops. Under the BEE project [16] some 22 regional energy potential studies for energy crops were analysed, in most of them the analyses were limited to the evaluation of surplus agricultural land, *i.e.* the land that is no longer required for the production of food and not needed for other purposes (*e.g.* for the protection of biodiversity or for infrastructure). Energy crops production potential is specific to regional parameters of crop cultivation (soil, climate conditions as well as irrigation and fertilisation demands), thus, estimated energy crops yields per ha will differ depending on agricultural/environmental conditions [19]. The most important criterion in the calculation is the choice of appropriate land use categories. At this stage the competition for food crop production or sustainability criteria are not included. The following land use categories are suggested:

- fallow land,
- kitchen gardens,
- meadows and permanent pastures,
- permanent crops,
- other agricultural land (not cultivated and not maintained in a good agricultural condition), and
- other lands.

The term "surplus land" is understood differently by many biomass studies [11]. The lack of indication for land use types, which can be dedicated to energy crops, is the main reason for

Table 3
Agriculture Land Quality Index, example of application in Poland.

Index	Range
Soil quality	18–95
Climate	1–15
Relief	0–5
Soil moisture conditions	0.5–5
LQI	19.5–120

Table 4
Agricultural Land Quality Index applied to differentiate maize crop yields.

LQI classes	LQI score	Qualitative evaluation	Maize yields in green mass Y [t ha^{-1}]
I	<50	Very unsatisfactory	35
II	50–59.9	Unsatisfactory	40
III	60–69.9	Average	45
IV	70–79.9	Good	50
V	>80	Very good	60

Table 5
Values assumed for the calculation of methane yields.

	Dry matter content	Organic	Specific methane yields	
	TS % $\dot{m}$	oVS % TS	M_{oVS} N m^3 CH$_4$ t$_{oVS}^{-1}$	M_{FM} N m^3 CH$_4$ t$_{FM}^{-1}$
Animal excrement				
Bovine (cow) slurry	10	80	210	14
Bovine (cow) manure	25	72	153	53
Pig slurry	6	80	250	12-17
Pig manure	22	77	432	45
Cattle manure	25	80	250	44-53
Poultry manure	40	75	280	82-90
Sheep manure/goat manure	60	51.3 54.6		59
Equidae (horses) manure	27	84	255	35-59
Energy crops				
Maize silage	33	95	340	106
WCC silage	33	95	329	105
Grass silage	35	90	310	98
Cereal grains	87	97	380	320
Sugar beet	23	90	350	72
Fodder beet	16	90	350	52

Energy crops continued M_{FM}: Corn cob mix (CCM) 242, Fodder beet leaf 38, Cereals (whole crop) 103, Cereal grain kernels 320, Grass including ley grass 100, Forage rye (whole crop) 72, Legumes (whole crop) 63, Grain maize 324, Ground ear maize 148, Maize (whole crop) 106, Sunflower (whole crop) 67, Sorghum (whole crop) 80, Sudan grass 80, Ryegrass 79, Sugar beet 75, Sugar beet leaf with sugar beet parts 46, Clover (as catch crop from arable land) 86, Legume mix 79, Winter beet 70, others not mentioned 50 N m^3 CH$_4$ t$_{FM}^{-1}$.

discrepancies in calculation methodologies. The following land use types are suggested to be dedicated to energy crop cultivation [10]:

- Unused agricultural (arable) land (surplus available after food and environmental purposes),
- low productive land (not suitable for conventional food crops),
- unprotected and underutilized lands, and
- unprotected grassland and woodland.

The energy crop yields are region specific, and can be calculated *e.g.* by using land and soil quality indexes. The national resources of soil maps and their assessments are not coherent across Europe, data on agricultural productivity is applied with a separate methodology in each EU member state, no uniform mapping schemes exist [20]. For example in Poland the Land Quality Index (LQI) reflects the potential for agricultural production, as controlled by natural conditions. Its primary objective is the creation of indicators for the quantitative and spatial assessment of natural factors to estimate the crop productivity at the regional level. LQI is based on the assessment of factors ranked by assigning appropriate weights, reflecting the relative magnitude of their impact on land productivity: soil quality, climate, relief, soil moisture conditions.

LQI allows to differentiate *i.a.* the maize crop yields under given environmental conditions [21,22] (Tables 3 and 4).

In Germany a similar index is known as *Bodenklimazahl*, it reflects the natural environment potential for the agricultural production. This index measures the natural land productivity, from the quantitative point of view. Data are provided for Homogenous Spatial Mapping Units (HSMU) with a resolution of 1×1 km^2, with consideration of soil, slope, land cover and administrative boundaries as delineation features [20,23].

The calculation of theoretically available areas for biogas energy crop production can be performed for many different plant species; however, in order to simplify the regional analysis, energy possible to be obtained from 1 ha of land should be evaluated for the most viable crop. Maize is the most frequently used crop in Germany (a top EU agricultural biogas producer), it is characterised with the highest land-efficiency and the smallest amount of land required [23]. Its yield varies as per the agricultural/environmental conditions from 35 to 60 t$_{FM}$ ha^{-1} (45 t$_{FM}$ ha^{-1} on average) with average methane yields of 89–120 Nm^3 t$_{FM}^{-1}$, which indicates the levels of spatial methane yields in the range of 3100–7800 Nm^3 ha^{-1} (4700 Nm^3 ha^{-1} on average). Other energy crops are characterised with lower spatial yields, *e.g.* grass silage, green waste; or comparable yields – sugar beets: 3250–4560 Nm^3 ha^{-1} but they are problematic with handling [24]. Differences in calculations of energy crop potentials mainly result from differences in two parameters *i.e.* land availability (and quality) as well as biomass yield assumptions [10].

For energy crops theoretically available yields are derived from the following equation:

$$\dot{m}_{crop} = \sum_{i=1}^{n} A_i Y_i \qquad (2)$$

$\dot{m}_{crop}$ – regionally available amounts of energy crops per unit of time [t a^{-1}],
A_i – regionally available area for energy crop cultivation, under given agricultural conditions [ha] and
Y_i – yields of green mass estimated for the area A_i [t$_{FM}$ ha^{-1}].

2.2.1.3. Agrifood industry. For the agrifood industry the amounts of the regionally available feedstock potential will be derived from the regional waste statistics, split into waste codes. Unfortunately, it is a common case that it is not possible to obtain a more detailed information on waste characteristics due to statistical confidentiality of information derived from commercial entities.

Amounts of organic substrates $\dot{m}_{oVS}$ are calculated by multiplication of available fresh matter $\dot{m}$ by physical characteristic of

given feedstock (dry matter *TS* and organic matter content *oVS*):

$$\dot{m}_{oVS} = \dot{m} TS oVS \quad (3)$$

$\dot{m}_{oVS}$ – amount of organic matter per unit of time [t a^{-1}],
$\dot{m}$ – amount of fresh matter per unit of time [t a^{-1}],
TS – total solids content [%$\dot{m}$], and
oVS – organic matter content [% TS].

There, where information on amounts of substrates is not directly available but needs to be calculated, TS and VS data is crucial. In the case of animal manure it is calculated from the number of animals, information best accessible from regional statistics (Table 5) [26-30].

2.2.2. Calculation of the gas yield potential

In order to calculate biogas/methane production potentials, 3 substrate categories: animal waste, energy crops and agrifood industry waste are multiplied separately by specific biogas/methane yield values, characteristic for each substrate category.

Theoretical specific biogas yields can be calculated very precisely using equations developed by Buswell and Simons in 1930's and later modified by Boyle in 1970's; assuming that all organic matter is completely converted to biogas [25]. For each substrate the contents of carbon, hydrogen, nitrogen, sulphur and oxygen (C, H, N, S, and O) are split into protein, carbohydrates, and fat; which values are obtained either from substrate atlases or empirically. Provided that feedstock composition is known, the theoretically achievable gas yields can be calculated. In the EU Agrobiogas project [25] the theoretically calculated values were compared with the empirical data derived from fermentation tests for energy crops, for some substrates the convertibility rate was as high as 85% for others only *c.* 50%.

So far the practical application of the above mentioned method has been very limited due to the fact that such details are not available for all substrates [25,26]. It was assumed that for a regional study it will be easier to use empirical values of specific methane yields (M_{oVS}) for both theoretical and technical potentials. It is justified by the fact that the amount of work to obtain detailed information based on theoretical equations does not entail higher data accuracy and the usability of final results.

Another important issue is the decision whether the results will be presented as biogas yields or methane yields. Due to the fact that the content of methane (CH_4) in the biogas varies from substrate to substrate, calculating the energy potential in methane (CH_4) units facilitates the calculation process. The methane yield potential $\dot{Y}_{CH4}$ is calculated for each substrate category either by

- Multiplying the amount of organic matter content $\dot{m}_{oVS}$ by specific methane yield based on organic matter content M_{oVS}:

$$\dot{Y}_{CH4} = \dot{m}_{oVS} M_{oVS} \quad (4)$$

or by,

- Multiplying the amount of fresh matter $\dot{m}$ by a specific methane yield based on fresh matter M_{FM}:

$$\dot{Y}_{CH4} = \dot{m} M_{FM} \quad [5]$$

$\dot{Y}_{CH4}$ – methane yield per unit of time [Nm^3 CH_4 a^{-1}],
$\dot{m}_{oVS}$ – amount of organic substrate per unit of time [t a^{-1}],
$\dot{m}$ – amount of fresh matter per unit of time [t a^{-1}],
M_{oVS} – specific methane yield on organic matter (*VS*) basis [Nm^3 CH_4 t$_{VS}^{-1}$], and
M_{FM} – specific methane yield on fresh matter (*FM*) basis [Nm^3 CH_4 t$_{FM}^{-1}$].

2.2.2.1. Animal manure and energy crops.

The characteristic data on specific methane yields (M_{VS}) needed for such calculations are derived from the literature survey (Table 5) [26-30].

2.2.2.2. Agrifood industry.

The list of wastes from the agrifood industry for anaerobic digestion, using the nomenclature of the EU Waste Catalogue, EWC [31], has been stipulated in the European Commission's communication [32]. Table 6 presents specific methane yield values M_{FM} for agrifood industry [28,33]. However, such a detailed breakdown of EWC is handier to use on a project level (*e.g.* while calculating substrates for a biogas plant in a given location). For the purpose of regional analyses it is very difficult to couple individual M_{FM} data with the available statistical information. Therefore, it is suggested to aggregate M_{FM} [Nm^3 CH_4 t$_{FM}^{-1}$] values for the second level data of the EWC, assuming the following aggregated values: 50 [Nm^3 CH_4 t$_{FM}^{-1}$] for agricultural waste, meat industry (abattoirs and meat processing), fruit and vegetable industry; 90 for sugar industry and alcoholic and non-alcoholic beverages; 130 for milk industry; 230 for grain industry; and 110 for other wastes.

Methane yields for each substrate categories can be now added to obtain information on the total theoretical methane production in a given region:

$$\dot{Y}_T = \dot{Y}_{AW} + \dot{Y}_{EC} + \dot{Y}_{AFI} \quad (6)$$

$\dot{Y}_T$ – total methane yield per unit of time [Nm^3 CH_4 a^{-1}],
$\dot{Y}_{AW}$ – methane yield from animal manure per unit of time [Nm^3 CH_4 a^{-1}],
$\dot{Y}_{EC}$ – methane yield from energy crops per unit of time [Nm^3 CH_4 a^{-1}], and
$\dot{Y}_{AFI}$ – methane yield from agrifood industry per unit of time [Nm^3 CH_4 a^{-1}].

2.2.3. Calculation of the energy potential

The theoretical energy potential can be expressed in energy units by multiplying the total biogas yield $\dot{Y}_T$ by the methane calorific value H_i:

$$P_T = \dot{Y}_T H_i c \quad (7)$$

P_T – total regional theoretical energy potential for all substrates, per unit of time [PJ a^{-1}],
$\dot{Y}_T$ – total methane production, per unit of time [Nm$^3_{CH4}$ a^{-1}],
H_i – methane calorific value H_i [10 kWh (m^3)$^{-1}$], and
c – unit conversion factor (kWh to PJ) 3.6×10^{-9}.

2.3. Technical potential

2.3.1. Feedstock availability

The technical potential can be constrained, *i.a.* by the following parameters: technological (waste processing, energy conversion efficiency); spatial suitability, as well as environmental and legal constraints. The choice of parameters to be included as constraining factors for the calculation of the technical potential has been so far decided individually for a given location [14].

Table 6
Average specific methane yields for agrifood industries coupled with the EU Waste Catalogue codes.

Waste Code	Waste	Examples of M_{FM} [Nm^3 CH_4 t_{FM}^{-1}] specific methane yield average values	
02	Waste from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing		
02 01	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing	**Agricultural waste** 50 Nm^3 CH_4 t_{FM}^{-1}	
02 01 01	Sludges from washing and cleaning		
02 01 02	Animal-tissue waste		
02 01 03	Plant-tissue waste		
02 01 06	Animal faeces, urine and manure (including spoiled straw), effluent, collected separately and treated off-site		
02 01 99	Wastes not otherwise specified		
02 02	Waste from the preparation and processing of meat, fish and other foods of animal origin	**Meat industry (abattoirs and meat processing)** 50 Nm^3 CH_4 t_{FM}^{-1}	
02 02 01	Sludges from washing and cleaning	Guts (pork)	27
02 02 02	Animal-tissue waste	Animal blood	83
		Ruminal contents	33
02 02 03	Materials unsuitable for consumption or processing	Flotation fats	43
02 02 04	Sludges from on-site effluent treatment	Flotation sludge	81
02 02 99	Waste not otherwise specified	Grease separate contents	15
02 03	Wastes from fruit, vegetables, cereals, edible oils, cocoa, coffee, tea and tobacco preparation and processing; conserve production; yeast and yeast extract production, molasses preparation and fermentation	**Fruit and vegetable industry** 50 Nm^3 CH_4 t_{FM}^{-1}	
02 03 01	Sludges from washing, cleaning, peeling, centrifuging and separation	Apple pomace	100
		Fruit pomace	49
02 03 04	Materials unsuitable for consumption or processing	Fruit and grape marc (fresh/untreated)	9
		Vegetables (rejected)	40
02 03 05	Sludges from on-site effluent treatment	Vegetable trailings	26
02 03 99	Waste not otherwise specified	Medicinal and spice plants (rejected)	58
		Potato waste water from starch production	11
		Potatoes (rejected)	92
		Potatoes (pulped, medium starch content; not or no longer suitable for consumption)	66
		Potato processing water from starch production	3
		Potato pulp from starch production	61
		Potato peels	66
		Potato juice	30
02 04	Wastes from sugar processing	**Sugar industry** 90 Nm^3 CH_4 t_{FM}^{-1}	
02 04 02	Off-specification calcium carbonate	Molasses from beet sugar production	16
		Press cake from sugar production	6
		Sugar beet shavings	64
02 04 03	Sludges from on-site effluent treatment	Small beet pieces (from sugar processing)	64
02 04 99	Wastes not otherwise specified		
02 05	Wastes from the dairy products industry	**Milk industry** 130 Nm^3 CH_4 t_{FM}^{-1}	
02 05 01	Materials unsuitable for consumption or processing	Buttermilk fresh (not or no longer suitable for consumption)	32
		Casein	392
02 05 02	Sludges from on-site effluent treatment	Skimmed milk fresh (not or no longer suitable for consumption)	33
02 05 99	Waste not otherwise specified	Skimmed milk dry	363
		Milk (not or no longer suitable for consumption)	70
		Lactose	378
		Lactose molasses	91
		Lactose molasses low protein	69
		Curd cheese (not or no longer suitable for consumption)	924
		Acid whey	2
		Acid whey fresh	20
		Rennet whey	44
		Rennet whey fresh	18
		Whey	18
		Whey, low sugar, dry	298
02 06	Wastes from the baking and confectionery industry	**Grain industry** 230 Nm^3 CH_4 t_{FM}^{-1}	
02 06 01	Materials unsuitable for consumption or processing	Old bread	254
		Baking waste	344
02 06 03	Sludges from on-site effluent treatment	Spent grains (fresh/pressed)	61
		Cereals (trailings)	254
		Cereal waste	272
		Grain dust	172
		Bran	270
02 07	Wastes from the production of alcoholic and non-alcohol beverages (except coffee, tea and cocoa)	**Alcoholic and non alcoholic beverages** 90 Nm^3 CH_4 t_{FM}^{-1}	
02 07 01	Wastes from washing, cleaning and mechanical reduction of raw materials	Potato vinasse from alcohol production	17
		Cereal vinasse from alcohol production	18
02 07 02	Wastes from spirits distillation	Brewer's dried grains	112
02 07 04	Materials unsuitable for consumption	Grape pomace	260
02 07 05	Sludges from on-site effluent treatment	Fruit stillage	30
02 07 99	Waste not otherwise specified		

Table 7
The availability of agrifood waste as input material for biogas plants.

Agrifood wastes	Availability
Beer production	25–40%
Biodiesel production	10%
Sugar production	1%
Fruit juice production	25–50%
Wine production	10–20%
Meat processing	70–75%
Vegetable growing and processing	8–20%
Food waste	50%
Grain and fibre processing	80%
Food processing	65–75%

Following sustainability issues can be reflected in the technical potential [11]:

- environmental sustainability (biodiversity, climate change, soil, water, air quality, resource use),
- social sustainability (competition with the demand for food, feed and fibres; labour conditions), and
- economic sustainability (bioenergy costs).

2.3.1.1. Animal manure. The calculation of the technical potential is suggested to be limited to only chosen breeding animals: poultry, pigs, cows kept under shelter for most of the year; for other animals the collection of waste has proven to be technically difficult. Another limiting factor is the farm size (*e.g.* only farms above certain size) an its typology such as production profile (plant or animal production) [14,34]. The usability of animal excrements was evaluated for Greek conditions: 45% for cattle manure and 80% for pig manure [13]. However, for each region such coefficients should be chosen individually, other authors indicate 75% for cattle manure, 90% for pig slurry and 75% for poultry manure [35]. In Germany cattle, chickens and turkeys are kept in stables 68% of the time (85% during the 4 winter months and 60% during the rest of the year), 100% of pigs were assumed to be in stables [16].

2.3.1.2. Energy crops. For energy crops the potential can be limited by the maximum crop cultivation area. As the example of Germany shows, energy crops can become competitors for land with food dedicated crops. For modelling purposes, future constrains need to be introduced, in order to guarantee that energy crops do not develop beyond a certain unsustainable limit. In Germany 850,000 ha (below 5% of the total 17 million ha agricultural area) is used for the cultivation of biogas crops [36]. However, the situation is region specific; in some German federal lands the share of maize as an input material for biogas plants exceeded 20% of arable land, *e.g.* in Schleswig–Holstein: 26% [23]. For Sweden the following limiting factors were considered: 10% of arable land (out of which 25% is dedicated to biogas dedicated crops) and 50% of the fallow land of which 100% is used for biogas [37].

2.3.1.3. Agrifood industry. The organic waste from agrifood industry (AFI) is often used by other entities such as animal fodder or fertiliser in agricultural fields, only a fraction of the total generated waste is disposable for biogas production. The technical availability of feedstock from AFI waste was described for chosen sectors. For Sweden, an average 54% of all waste was assumed to be available for the technical potential of the biogas production [37]. The season of production is also important, if fruit and vegetable wastes are used for anaerobic digestion, solutions allowing to extend the period of their usability must be considered (beyond 2 months window of crop harvest), *e.g.* via the storage. Indicative values of the limiting factor (*LF*) expressed as the feedstock availability for anaerobic digestion are presented in Table 7 [14,38].

The limiting factors (*LF*) should be introduced while estimating the technically available amount of feedstock, $\dot{m}_{tech}$:

$$\dot{m}_{tech} = \dot{m}\, LF \tag{8}$$

$\dot{m}_{tech}$ – technically available amount of substrates per unit of time [t a^{-1}],
$\dot{m}$ – amount of substrate per unit of time [t a^{-1}], and
LF – limiting factor for a given substrate.

2.3.2. Conversion technologies

The technical potential includes the energy conversion rates [13], *i.e.* the efficiencies of the conversion of the input energy contained in feedstock to energy output: *via* biogas to other energy carriers (heat, electricity or transportation fuel). As far as the biological process of anaerobic digestion is concerned (conversion to biogas *via* fermentation); for simplification it can be assumed, that the energy contained in the feedstock equals the technical potential for biogas production. It is due to the fact that for calculation of both potentials specific methane yields M_{CH4} are taken from the substrate atlases (empirical rather than theoretical data).

The most popular, among available energy conversion technologies (from biogas to other energy carriers), is the cogeneration, *i.e.* the combined production of heat and power (CHP). For simplification the same energy conversion rates can be assumed, disregarding the plant size, [38]. However, it must be remembered that in the reality the efficiency of a CHP changes with the engine's size. Therefore, it is more accurate to differentiate between CHP sizes:
- Suggested values of electric efficiency: η_{el} 150 kW_{el} 35%; 500 kW_{el} 37.5%; 1000 kW_{el} 39.5%; 2000 kW_{el} 41.7% [23],
- or by other authors: electricity: η_{el} 33–40% (microgas turbine: η_{el} 28%); and for CHP heat: η_{th} 48–50% (microgas turbine: η_{th} 54%) [39].

In order to estimate the final energy output, the plant's process energy (internal energy consumption) should be deduced from the total energy production. By the process energy it is understood *i.a.* the heat use to maintain the fermentation process inside of the digester, electricity used for mixing, and other energy demanding processes such as biogas purification. Additional technological modules can be also added to the plant, such as dewatering and granulation devices for commercial sale of produced digestate as a consequence more process energy will be consumed. Other energy losses are connected for example with the heat delivery: 3.5–4% of the conveyed heat for the 0.5–2 km heating network [39].

The energy conversion rates can be included in the calculation of the technical potential (expressed in electricity units) by using the following formula:

$$P_{el} = P_{in}\eta_{el}(1-q_{el})c \tag{9}$$

P_{el} – technical energy potential for the production of electricity per unit of time [GWh a^{-1}],
P_{in} – energy input potential per unit of time [PJ a^{-1}],
η_{el} – efficiency for the power production [%],
q_{el} – fraction of the electricity used for biogas plant's process energy [%], and
c – unit conversion (PJ to GWh) 0.0036.

or expressed as heat production:

$$P_{th} = P_{in}\eta_{th}(1-q_{th})/1000 \tag{10}$$

P_{th} – technical energy potential for production of heat [TJ a^{-1}],
P_{in} – energy input potential [PJ a^{-1}],
η_{th} – efficiency for heat production [%], and

q_{th} – fraction of the heat used for biogas plant's process energy [%].

The technical potential can be expressed as a final energy (electricity, heat) or as cumulated capacities in MW_{el} installed, the later is a more adequate unit to present results on the regional level. The total expected installed capacitates are obtained through the division of the electricity production (P_{el}) by the expected number of working hours during the year (usually between 7500 and 8000 h [23]).

$$P_{MW} = P_{el}/h \tag{11}$$

P_{MW} – technical potential expressed as total expected installed capacitates [MW_{el}],
P_{el} – technical energy potential for the production of electricity [GWh a^{-1}], and
h – assumed number of working hours during the year [h].

Technical and economic potentials are calculated separately for plants' size ranges due their varied technical and economic characteristics. It is proposed to use a uniform division into small and large units; whereas, the size ranges need to be established individually for each region. Authors suggest a 150 kW_{el} threshold for small size units; 500 kW_{el} for medium; 1000–2000 kW_{el} for large ones [35,40,41]. Whereas, a German model designed especially to stimulate the diffusion of biogas plants on the regional level introduces following thresholds: 75, 150, 500, 1000 and 2000 kW_{el} [23].

In most countries it is the design of support policies on the national level, which finally justifies such a division. For example in Germany, the most mature European arena for agricultural biogas plants, with its EEG [42] RES support policy, the plants smaller than 70 kW_{el} in 2009 made 17% of all capacities installed, in the range of 70–500 kW_{el} 66%, and 17% for larger units. However, there are regional deviations from the average values: in Brandenburg (east of Germany), where large collective farms dominated during the communist times, the majority of plants had capacities above 500 kW_{el}; whereas; in Bavaria with its small farms structure the capacities were usually below 150 kW_{el}. On the other hand, the number of installations was higher in Bavaria: *c.* 2000 plants *vs. c.* 200 units in Brandenburg [43].

The size of a plant depends both on substrates fed to the biogas plant and the farming structure: micro-biogas plants are usually farm integrated. Whereas, utilisation of co-digestion substrates from agrifood industries seems to be preferred by larger plants. Bigger plants are organised in a manufacturer/waste company/utility model using industrial organic waste as an input material, whereas, small plants are rather operated by farmers using animal excrements with admixture of household organic wastes and energy crops [44].

2.4. Market potential

The technical energy potential does not include information on the market demand for biogas plant's final products (heat/electricity/transportation fuel or grid fed biomethane). The demand for such products is highly dependent on possibilities to integrate a given plant with the existing infrastructure, and this is reflected in the calculation of the market (economic) potential. This potential is related to the economic and legal factors, which are shaped by the national framework.

The market potential of agricultural biogas plants includes both the spatial (sub-regional breakdown) and temporal dimensions (short, medium and long-term), in which potentials are coupled with profitability indicators, political support policies and infrastructural conditions [14]. The market potential is further split into a short term available potential and the implementable long term potential. The first one is considered as a starting capital, leading to the implementation of the first projects under a given political framework; whereas, the implementation of a long-term potential requires optimisation of the existing structures [4].

The economic potential was calculated for German regions. One example was Bavaria (currently *c.* 1700 agricultural biogas plants, with the total of 422 MW_{el} installed capacities and an average power of 250 kW_{el} per plant): in the next 20 years, the construction of additional 400 biogas facilities, with a cumulative electric capacity of *c.* 200 MW_{el} was envisaged: in 2030 the aggregate generating capacity amounts to *c.* 600 MW_{el}, with a total of *c.* 2100 plants [35]. Although with the currently planned (2014) changes to EEG2012 (a German Renewable Energy Act) and its technology capacity thresholds of 100 MW per annum for the whole of Germany this scenario seems not to be feasible any longer.

The future market can be envisioned by the formulation of narratives; whereas, the technology development is determined by the identification of the following scenario parametric groups [41]:

- *External factors*: economic (*e.g.* national support mechanisms and the competition with other sources), national policies (*e.g.* environmental, agricultural),
- *Endogenous factors*: regional policies, infrastructural conditions, and
- *Targets and boundaries for future developments*: the elaboration of action plans and policy milestones.

2.4.1. External factors

The external factors, in particular national support policies, set boundary conditions for the development of biogas plants. Biogas plants' size ranges (small, medium, and large) are likely to develop in line with the designed regulatory framework. The EEG 2004 (former version of the German Renewable Energy Act) was best suited for the development of capacities above 500 kW_{el}; whereas, the change of the regulatory framework (EEG 2009) led to the expansion of smaller plants with the capacity of 150 kW_{el}. Not only plant's size can be impacted: due to the design of EEG 2009 energy crops increased beyond expectations their share as a feedstock for biogas production, under the EEG 2012 [42] other substrates are promoted. The regulatory framework can also impact the use of final energy produced in biogas plants, the EEG 2012 compared to EEG 2009 favours the use of heat [23].

2.4.2. Endogenous factors

Future narratives referring to the endogenous (regional/local) factors should contain the following design elements [41]:

- the economic availability of a waste feedstock used as an input material,
- energy crops cultivation acreage for dedicated areas,
- the proportion of biogas dedicated for different conversion technologies (cogeneration, heat only boilers HOB, or new entrant technologies such as biomethane for the natural gas grid or fuel cells) and their diffusion (number of plants split up into size ranges),
- the infrastructure – the absorption capacity or indication of needs for extension,
- the organisational structure in rural areas,
- actors involved and responsible for implementation of policies, and
- setting clear, ambitious but realistic targets.

General questions for the formulation of scenario storylines can be enriched by more detailed feedstock, technology and infrastructure deployment questions (scenario formulation design questions):

- What is the role of regional authorities in the organisation of the process of planning and by which regional policies can the assumed targets/objectives be achieved?
- What clustering activities should be undertaken on the regional level, who should participate and initiate them and what are the expected benefits?

For the above mentioned groups of endogenous factors, the literature review indicates the most crucial elements of the designed, future market, which are listed below.

2.4.2.1. Waste feedstock availability. In long term horizons the change in livestock populations should be considered, for example a decreasing trend in the number of animals was assumed for Sweden [37].

The feedstock price together with its transportation costs (acquisition costs) play a crucial role in the regional economic evaluation. Feedstock sustainability criteria should consider the overall system efficiency (preference should be given to locations, which are closest to the feedstock generation) [40]. Due to economic considerations the rule of the thumb should be: the more water the feedstock it contains the shorter transportation distances should be. The maximum transportation distance for agrifood industrial waste is assumed at 10 km for substrates in a liquid form (6–10% of the dry matter content) and 20–50 km in a solid form (more than 20% of the dry matter content) [45,46].

Diffusion of plants' different size ranges correlates heavily with the feedstock availability around the biogas plant. Thus, in the regional diffusion stimulations such factors should be correlated [40]. In regions, where the market is already saturated with agricultural biogas plants *i.e.* with higher demands for a feedstock, longer delivery distances determine the price of input material, thus, the price is likely to increase [19,40]. The analysis can take into account feedstock supply curves. For instance the supply price for maize varied from €20 to €53 per ton depending on the local production and opportunity costs, related to the competition for land between different crops, as well as feeding and fertiliser substitution values [23]. For materials previously considered to be available for free (*e.g.* industrial organic waste) a gate fee can be demanded in the future, as the market becomes more mature and saturated. The feedstock price will follow the demand–supply pattern: when the entire potential is still available, the feedstock costs are estimated at 17.5€/t; when half of it has been used up at 35€/t, and when the whole at 52.5€/t [35].

Scenario formulation design questions:

- What changes are foreseen in the future supply of the feedstock: quantities and types of substrates, sub-regional distribution?
- Will changes in the regional agriculture and economy impact the amount of feedstock delivered to a biogas plant?
- How will changes in the substrate acquisition price impact the profitability of the plant: gate fee, the increase of the local demand for biomass, the competitiveness with other energy sources?

2.4.2.2. Energy crops cultivation. The long term evaluation of energy crops in the context of sustainability should be envisioned [40]. Issues such as the competition for land between energy and food crops, as well as the necessity to decrease acreages likely to be dedicated for monocultures, have become a public acceptance issue in some "biogas regions", *e.g.* in Lower Saxony, Germany. In order to maintain the long term sustainability principle the upper limit for acreages dedicated to energy crops must be defined, it is suggested to set this value at the maximum of 20% of arable land [41]. The price for energy crops depends on local conditions such as soil/climate, field labour costs, demand for irrigation and fertilisation. Due to the above, in order to optimise the sitting process, sub-regional feedstock demand curves can be useful [40]. Other issues relating to the future can include interdependence between animal production and land availability for energy crops: for Ireland a decreasing animal production was envisioned followed by decreasing acreages for grassland areas, and as a consequence an increased land availability [45].

The energy production costs for (*i.a.* biogas projects) depend not only on the investment costs but first and foremost on the O&M costs expressed by substrate prices (as fuel for biogas plant). Therefore, although the investment costs can be expected to drop overtime, the substrate acquisition costs are likely to increase (especially in the case of energy crops).

Scenario formulation design questions:

- What kind of agricultural land will be dedicated to energy crops in the future (arable land, set-aside land, grasslands)?
- What will be the ultimate proportion of arable land dedicated to energy crops in order to maintain long term sustainability criteria and exclude the competition for land with food crops?
- Will the farming for energy crops be intensive or extensive (monoculture or crops rotation)?

2.4.2.3. Infrastructure/electricity grid. Many authors indicate the need to elaborate a methodology to evaluate RES potential by their integration with the transmission and distribution networks. Planning of a grid extension for dispersed power generation is a very complicated task, requiring high spatial resolution data and co-operation between spatial planners, power engineers and economists [47]. In many cases in Germany RES connected exceeded the regional power load, which can lead to damages of infrastructure and blackouts [48]. Thus, envisioning biogas as a storage medium can actually contribute to the improvement of the planning process thanks to equalisation of loads and elimination of voltage fluctuations, when simultaneously used with other intermittent sources such as PV or wind [49,58].

The biggest problems can be expected from low voltage networks (LV), designed decades ago, not envisioned to feed in new generation capacities. The LV transformers very often need uprating and upgrading for the uptake of dispersed power generation. Especially voltage fluctuations can be dangerous and lead to accidents when power delivered exceeds the network's load, therefore, spatial power load forecasting is crucial in grid planning [50]. LV infrastructure can accommodate as much as 200% of the local load [51], for the medium voltage (MV) infrastructure a single node principle should be the first rule [52]. However, the single-node approach has been criticised to be imprecise and with usability limited to very preliminary calculations [53].

For the electricity grid expansion, future scenarios should include information such as the temporal dimension of new capacities, the regional load forecasting, the proximity of nodes to the power generation and distribution points [50]. Such future planning should include supply–demand strategies for energy balancing. The timeframe for the planning of the extension of distribution grids should be matched with the time usually required for such works: up to 5 years for infrastructure at the consumer site, 15 years for distribution feeders, 20 years for planning of a new MV substation; whereas, higher voltage infrastructures require more time for planning: over 20 years [54].

2.4.2.4. Infrastructure/heating network. In agricultural areas it is very difficult to find a stable demand for the uptake of heat produced in CHP units. Due to the fact that gross heat production in the cogeneration is not fully covered by the demand, the overall efficiency of the whole agricultural biogas plant seldom exceeds

60% [44]. The integration of biogas plants with the existing heat demand infrastructures is crucial for the calculation of regional economic potentials [55]. It is proposed to evaluate the possibility to locate large industrial biogas plants in a reasonable vicinity to settlements and other agricultural activities (drying, heating of greenhouses *etc.*), which could be a solution to couple heat demand with heat supply [41]. A focus can be also on the expansion of the rural micro-heating networks [56].

2.4.2.5. Infrastructure/gas grid. The biomethane (to be fed to the gas grid) generation from biogas must be coupled with the evaluation of regional natural gas infrastructures, both existing and planned. For instance Ireland can boast a well-developed natural gas infrastructure, additionally supported by an appropriate farming culture [45]. Due to economic reasons besides grid accessibility constraints, it is the size of production which matters: projects are considered feasible from 100 $Nm^3 h^{-1}$ of raw biogas production. Also matching the distances required for the transportation of substrates with the distances to the natural gas grid injection point, has an impact on the economic evaluation of the plant: the maximum distance is suggested to be not exceed 20 km [45].

Scenario formulation design questions:

- What method will be chosen to evaluate the capacity of the existing energy infrastructures to accommodate the energy produced by agricultural biogas plants?
- What infrastructure data is available and what will have to be estimated?
- How will the existing energy infrastructure integrate dispersed energy generation, what are the necessary extensions?
- Will the biogas plants, as a power balancing source, help integrate other intermittent energy sources (PV, wind) if their share in electricity generation exceeds certain limit (*e.g.* 30%)?
- How will new biogas technologies impact the future market?
- What external factors have an impact on grid operators to incorporate the rapid development of RES, and in particular agricultural biogas plants?

2.4.2.6. Digestate utilisation. The estimation of the market potential for the digestate as a fertiliser has an impact on the overall economic viability of the project. The production of digestate from larger biogas plants very often exceeds its uptake and utilisation possibilities as a fertilizer to be used on nearby fields: a 500 kW_{el} plant requires 350–500 ha of land for fertilisation [46]. The farm production profiles very often do not match the spatial distribution of digestate generation: the supply of substrates and demand for digestate as a fertiliser are very often distanced geographically. Therefore, on a regional level it is challenging to determine the supply/demand strategies for large amounts of digestate from biogas plants. Also, the organisation of farms and their production profile matters – if the animal production dominates, problems with spreading manure as a natural fertiliser will emerge, thus, impacting the transportation costs. In locations, where there is no crop cultivation (low digestate stocking capacity), the biogas plant will pay for the transportation of the digestate, thus increasing operational costs [40]. The market potential for the produced raw digestate as a fertiliser can be expressed as a function of distances from a plant to fields, if the digestate is further processed to produce fertiliser in a solid form (pellets), the biogas plant is likely to be less dependent on transportation distances.

The amount of digestate depends on the material used for the fermentation. Smaller weight volumes of energy crops are required to produce the same amount of energy, compared to animal excrements (characterised with lower energy values). For sustainability reasons the rule of the thumb is that the energy crops should not exceed 60% of the substrates' mass volume. For further modelling a 50–50% proportion is considered; thus for a 0.5 MW_{el} plant will require annularly *c.* 10,500 t_{FM} of maize silage and swine slurry, in total 21,000 t_{FM}. For each MW_{el} installed capacity it can be assumed that 42,000 t of digestate will be produced.

In order to estimate the required acreage A_{dig} for spreading of a biogas fertiliser it is assumed that the digestate (a mixture of maize silage and animal excrements) contains 4.1 kg N/t_{FM} of total nitrogen (N-tot) [24]. The maximum dosages of total nitrogen (N-tot) allowed per arable land acreage vary from country to country but are usually at the level of 170 kg N/ha [57]. It means that the total area for spreading the produced digestate will be calculated using the following formula:

$$A_{dig} = m_{dig} 4.1/170\ \dot{m}_{\boldsymbol{livestock}} = LSU\ Q_s(Q_m) \tag{12}$$

A_{dig} – area dedicated for spreading of the digestate [ha],
$\dot{m}_{dig}$ – production of digestate per unit of time [$t_{FM}\ a^{-1}$].

Scenario formulation design questions:

- Will the areas available for the crop cultivation be sufficient to absorb large quantities of the produced digestate, in the situation of abundance of biogas plants in one area?
- How many farmers will have to be engaged in the uptake of the digestate?
- Will it be recommended to separate digestate fractions into wet and dry fractions and transport it in the form of fertiliser pellets over longer distances, rather than to use the digestate locally?

2.4.2.7. Organisational structure in rural areas. There are various organisational models for agricultural biogas plants; distinguished are a farmer model, a manufacturer model, a waste company model, a utility model or a new comer model. Such organisational models are characterised by different plant sizes and feedstock: *e.g.* a plant operated in a farm model is usually small and does not use industrial agrifood waste as a feedstock [44]. Due to the choice of least cost options, big biogas plants are more likely to develop on larger farms, where availability of feedstock is higher [40].

In more mature markets it becomes common for farmers to organise themselves into purpose dedicated units (cooperatives) for a joint delivery of substrates or/and operation of a biogas plant [44]. In regions where the farm structure is fragmented the emergence of a new farming economy must be envisioned, where small farms can aggregate horizontally to jointly deliver feedstock and operate one agricultural biogas plant and its infrastructure (*e.g.* microgids). A system by which farmers change into prosumers of energy heralds the emergence of a new energy paradigm in rural areas.

Scenario formulation design questions:

- How will the so-far organisational structure in rural areas change in the future (farm's production profile: crop/animal, acreages, ownership structures) and how will it impact the development of agricultural biogas plants?
- How can local farms be incorporated into new energy solutions (using surplus of energy produced on site, cooperation *via* village microgrids, clustering for joint production of crops and operation of a biogas plant)?

2.4.2.8. New technologies and their diffusion. The most common technology for biogas conversion is the heat and electricity production in a cogeneration process (CHP); however, the

technological progress should be also accounted for. CHPs can lose their predominant role in the future time horizon. Other emerging applications and their adaptation to the existing infrastructure should be accounted for in mid and long term perspectives. New market entrants (such as energy storage, biomethane, microgrids, fuel cells, electric vehicles *etc.*) should be incorporated in future narratives [58].

For the purpose of the formulation of long term visions the technology diffusion theory can be used. The diffusion pattern assumes that in the long term the technology will develop along an S-curve, after an initial slow development (short term vision), it surges into the maturity phase (medium term vision) and after reaching the saturation point (due to market limitations) it finally slows down (long term vision) [59]. In long term regional analyses, in order to integrate the temporal dimension, the calculation can also contain information on the conversion efficiencies for other future entrant technologies; such as biogas to biomethane/hydrogen, fuel cells application [44]. Overall higher efficiency of the energy conversion as well as expected decreasing investment costs can trigger their development [39]. The development speed of innovative technologies improves over time, which is associated with the learning-by-searching, learning-by-doing, learning-by-using, learning-by-interacting, upsizing (or downsizing) a technology and economies of scale [60].

Scenario formulation design questions:

- For which market areas will CHP still remain the most popular biogas conversion technology?
- Which new entrants will emerge on the market (*e.g.* biomethane, microgrids, energy storage, biogas cars, hydrogen based fuel cells) and at which point of time, which market niches will be taken over by them?
- What will be the application time for the inception/maturity/saturation phases for small/medium/big agricultural biogas plants?

2.4.2.9. Regional added value. The regional added value can be of economic, social and ecological character, the first one can be expressed in monetary terms; however, the other two are not easily accountable. The starting point to identify the regional added value is always to calculate resource potentials. Such calculations can be used for instance to present local benefits and increase the social acceptance towards infrastructural investments [61]. However, it is suggested to calculate both the gross and net added values, with the consideration of also negative effects such as job replacements in other branches in the region and emissions caused by biogas plants themselves [4].

Economic added value: the regional economic added value is expressed by financial flows, which are kept in the region by means of compensation of fossil fuels, including: capital investments in new capacities, personnel (job placements) costs for operation and maintenance, costs of fuel, additional manufacturing base for the equipment [4,5]. In Germany, the turnover of the biogas industry in 2011 amounted to 6 billion EUR [36]. The calculation of the regional added value is based on the assumptions that each kW_{el} of installed capacity generates additional regional income: for a 150 kW_{el} biogas plant 600–800 EUR/kW_{el} and for a 450 kW_{el} plant 350–450 EUR/kW_{el} have been assumed [61]. Other indirect effects can also be included, thus, contributing to the economic activation (other regional indirect activities around the investment) [4]. The annually EU turnover in the biogas sector in 2011 was estimated at over 5 billion EUR [5], on a regional level *e.g.* in Lower Saxony 2.5 billion EUR investments in rural areas have been made since 2002.

Social added value: agricultural biogas plants are supposed to contribute to the economic development of rural areas by generating a local turnover and employment, encouraging the local entrepreneurship, and developing a local infrastructure. An important indicator for assessing the regional added value is the additional employment, because it has an indirect effect on all other aspects of life, both social and economic. Local jobs are expected in the production and logistics of energy crops, as well as the operation and maintenance (O&M). It is estimated than in 2011 over 71,000 have been created in the EU in the biogas sector [5], of which the majority belongs to agricultural biogas, the biggest share 40,000 jobs taken by Germany (incl. 10,000 for O&M) [36]. On a regional level in the German Lower Saxony the biogas support scheme led to the engagement of 3000 farmers, and 1500 direct (plus 5000 additional indirect) work places [62]. The calculation of the local employment, associated with the agricultural biogas, is based on the following assumptions:

- The harvest of energy crops: for maize each ton is estimated to require 0.27 h/t worker-hours or 4.9 h/ha, for countries where the mechanisation of agriculture is lower the values will be higher [71].
- O&M: it is estimated that the labour requirements for a 500 kW_{el} unit amount to 250 man days, or 1.14 man years, which is equal to a labour requirement of 4 hours per kW_{el}. However, smaller plants are expected to have higher labour requirements per kW_{el} [63]. For a 150 kW_{el} the amount of work was estimated at 6–7 h/kW_{el}/a, for a 450 kW_{el} 3–3.5 h/kW_{el}/a, and for 800 kW_{el} 2.3–2.8 h/kW_{el}/a [36,64].

Ecological added value: as the main product of agricultural biogas plants is electricity production, for simplification only CO_2 reductions from the power sector are considered as an environmental indicator. In Germany in 2010 the annual emission reduction of CO_2 due to agricultural biogas plants amounted to 120 $MtCO_2$ [36]. For this purpose the calculated MWh of produced electricity can be multiplied by the g CO_2/kWh indicator from the domestic power sector. Such aggregated indicators are published by the International Energy Agency for every country. [65]. The future perspectives for the energy intensity of the power sector can be obtained either from national projections, and in the case of lacking information from the IEA's world projections to 2050 [66]. Such an approach has been applied by many climate investments institutions to calculate the CO_2 abatement levels for international funding of renewable energy projects. However, it must be remembered that the generation of biogas also causes emissions: 290 g of CO_2 per each kWh produced [36], which should be deducted in order to calculate the net reductions. Other environmental indicators are more difficult to calculate on a regional level but can also be included, *e.g.* the emissions reduction from utilisation of heat and agriculture (methane CH_4 and nitrous oxide N_2O emission reduction from digested manure, replacement of organic fertilisers *etc.*) [4].

2.4.3. Formulation of scenarios for the market potential calculation

A scenario is not a forecast of the future, it reflects an internally consistent story about the path from the present to the future. A collection of scenarios can be described as a future map, it should be characterised with plausibility and internal consistency; the emergence of the future should be based on the past and the present situations. Scenarios can be described as comprehensive ideas, against which plans and strategies can be elaborated [67].

The answers to the design questions, mentioned in the previous chapter, can be obtained for a given region by different methods, such as

- review of statistical information, policies, reports, SWOT, and own analyses,

- interviews with regional key market players in the form of qualitative interviews or foresight studies,
- scenario building workshops or expert panels, and
- expert evaluations.

Involving other actors in the elaboration of future narratives allows to involve wider audience in the planning process. The outcome of the exercise leads to the formulation of the most probable technology development futures in a given region [41], as well as to the elaboration of technology dedicated regional road maps and action plans (dispersed generation/renewable/biogas) and their integration in the form of a decision toolkit with the regional development and spatial policies.

The elaboration of scenarios, especially in the mid and long term perspective, can be used not only by the regional authorities but also by infrastructure operators (electricity, gas grids, heating network) in order to formulate their future investment plans/ manage risks in the face of a growing market penetration of dispersed energy generation [53]. However, the current procedure, of *e.g.* electricity grid planning, has been to neglect the future high penetration levels of RES in the generation portfolio and to apply the principle of "connect and forget". Thus, the experience in the infrastructural integration of RES has been so far very modest [50].

3. Results and discussion

3.1. Delineation of the case study region

The Lubelskie region is one of 16 provinces (voivodships), NUTS-2 territorial units in Poland. It is located in the eastern part of Poland and covers the area of 2.5 million ha (3rd biggest province) with *c.* 2 million inhabitants and low population density 86 persons (km^{-2}). The Lubelskie Province is divided into 213 municipalities and 20 districts (counties), of which 4116 are rural localities and 41 cities (4 of which are city-counties). The region's economy is based on agriculture, with good soil and climatic conditions, it is one of the largest and most important agricultural regions in Poland, with well developed food production industry: fruit and vegetables, sugar, milling, dairy, meat, brewing, spirits and tobacco. It is also known for the production and processing of healthy, certified foods, and recently energy crops. The region's economy, besides the agriculture, is based on the chemical industry, wood and furniture, metal and engineering, including aerospace, the production of helicopters, tractors, agricultural machinery. It boasts of well developed research centres, young, well-educated professionals and favourable conditions for investment with special economic zones and industrial parks.

The agricultural character of the Lubelskie region makes it a natural arena for the development of biogas plants. The regional authorities chose this technology as one of the regional development priorities; further steps require translation of the political will, into strategic planning and formulation of policies. Farms are prevailingly small, fragmented, with a low concentration of livestock production, which can significantly restrict the future deployment of the biogas technology. The province has experienced social acceptance problems with new energy projects in rural areas, as the population is particularly reluctant to new infrastructural projects [71].

The utilisation of agricultural area is 1.66 million ha, which accounts for 66% of the total area of the province. The land use is dominated by arable land (75% share). Lands with a high share of permanent grasslands are located in the north-eastern districts. The province has favourable environmental conditions (climate, soil quality) for the production of feedstock for biogas plants. Unfortunately, in many cases they are offset by unfavourable agrarian structure and a low organisational level. In addition, a large area of the region (23%) is covered by different forms of environmental protection zones, which restrict the location and dynamics of new investments.

Table 8
The average size of farms in ha of Ulilization Agricultural Area (UAA).

Average farm size			Year
20–50 ha	**50–100 ha**	**> 100 ha**	
27.5	64.8	212.2	**2002**
30.1	67	257	**2010**
32.8	69	311	**2020***

* Data for the year 2020 is extrapolated from 2002 to 2010 trend lines.

The regional statistics from the Central Statistical Office (GUS), the Regional Spatial Planning Bureau and the Lubelskie Province Marshall's Office were aggregated to calculate potentials from biogas production and utilisation in the 20 subregions (counties) of the Lubelskie Province. For simplification of calculations, subprovinces were considered as separate economic entities [68]. The evaluation of biogas potentials has been carried out on the subregional level.

3.2. Theoretical and technical potential of the case study region

Theoretically the Lubelskie province has favourable conditions for the production of organic mass (animal manure, agrifood industry waste and energy crops), as an input for agricultural biogas. Unfortunately, the organisational structure of agriculture greatly reduces this possibility. It was estimated than there are only *c.* 340 holdings where the agricultural area exceeds 100 ha; *c.* 1200 for 50–100 ha and *c.* 9400 for 20–50 ha [69]. There is a tendency for the consolidation of land and increasing farms' sizes; however, it is still not enough to speed up the dispersion process of agricultural biogas investments [71] (Table 8).

In the region following industries are the most promising feedstock suppliers from agrifood industry: sugar, alcohol, dairy, meat, as well as fruit and vegetable processing. Entities producing over 1000 ton of waste per year (18% of all manufacturers) deliver 94% of the total waste volume. Unfortunately, when calculated into biogas energy potentials, agrifood waste streams are likely to have only a short term local, the total biogas energy volumes are not significant.

In 2010, the total power generation capacity in the region was 442 MW_{el} (1.2% of the domestic). However, the electricity consumption amounted to 5934 GWh, which means that 68% of the electricity demand was delivered from outside of the region [70]. Historically, the dependence on external electricity supplies has increased. The increasing demand for energy together with the absence of new generation sources creates a negative trend in security of energy supplies. This trend can be reversed by new generation capacities, in particular renewables (including agricultural biogas). It is expected that the potential for large investments will be met in the immediate vicinity of medium and high voltage infrastructures. In the longer term, grid feeding problems may emerge along with a rapid expansion of other RES, such as wind [71].

As far as the possibility of using agricultural biogas plants to produce biomethane fed to gas infrastructure is concerned, the feed-in capacity of natural gas distribution networks is sufficient in the region. Out of 41 cities in the Lubelskie province only 6 are not covered with the natural gas network. However, in the rural areas, access to the natural gas is limited, only 9.6% of rural households are connected (domestic average 17.6%). There are sufficient transmission reserves in the regional natural gas grid, however, taking into account the fact that biomethane projects are usually big and

capital intensive, the substrate base for such projects is rather limited – only a few biomethane projects are feasible [71].

Compared to the EU-27 average, the degree of land concentration and the livestock production in Poland is lower, additionally the Lubelskie Province has very dispersed farming structure. As a result, the development of large and medium agricultural biogas plants can be problematic. The involvement of smaller farms is a prerequisite for the dynamic development of agricultural biogas plants, however, it will be possible only if the horizontal consolidation of producer groups is encouraged, *i.e.* organisational measures in order to involve farmers in the production of energy crops. If such actions are undertaken even a few hundred MW_{el} installed capacities of agricultural biogas plants are feasible in the Lubelskie Province in the next 20 years [71] (Table 9).

Obtained results indicate a high usefulness of the applied method. For energy crops the theoretical potential was constrained by the environmental criterion: maximum 20% of arable land area in good practice can be dedicated to biogas energy crops.

The total theoretical potential of the primary energy produced from biogas in the Lubelskie Province is 172 PJ. Definitely the largest share belongs to energy crops (167 PJ), however, with regional discrepancies (Fig. 1). Świdnicki and Rycki (3.9 PJ) districts have the smallest potentials, and the largest belong to Biała Podlaska and Bialski (18.7 PJ). Districts with the lowest potential for the biogas production are characterised with a small Utilisation Agricultural Area (UAA). Significantly lower is also the share of farms with larger areas that could incur capital expenditures and provide raw materials for the biogas production. In some districts (Opolski, Świdnicki) low theoretical potential results from a low livestock density per hectare. In the case of Janowski district low potential may also be impacted by a significant share (63%) of environmentally protected areas. Districts, which are characterised by the biggest theoretical potential have the larger UAA and the number of larger farms >100 ha is bigger. In the case of Biała Podlaska and Bialski subprovince it is also a high livestock density (47.3 LSU ha^{-1}) and a low share (9%) of environmentally protected areas, which contribute to the large potential (Table 10).

The technical potential for primary energy production from biogas in the Lubelskie Province is also locally diverse (Fig. 1); in total it amounts to 70 PJ, of which 68 PJ is derived from energy crops. The smallest potential is ascribed to the districts of Rycki, Opolski and Janowski (0.6–0.7 PJ). Such results are a consequence of similar assumptions as described for the theoretical potential, *i.e.*: a small area of UAA, a large share of smaller farms and a large share of environmentally protected areas. In addition, in the case of a district of Opolski low theoretical potential may result from a significant share of UAA under permanent orchards cultivation. The largest technical potential belongs to districts with the largest UAA area: Biała Podlaska and Bialski, Chełm and Chełmski, Lublin and Lubelski, Hrubieszowski and Zamość and Zamojski (6.2–9.7 PJ), where a high share of larger farms is a decisive factor. Similar to the theoretical potential the district of Biała Podlaska and Bialski, it is highly influenced by a high livestock density and a low share of environmentally protected areas.

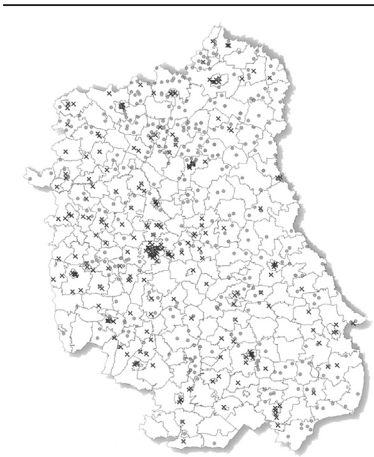
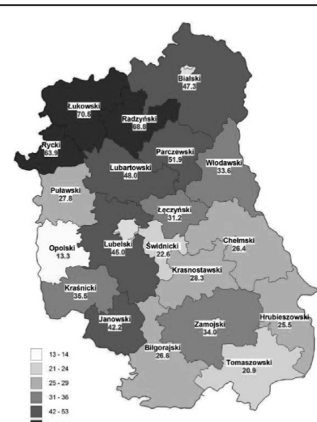
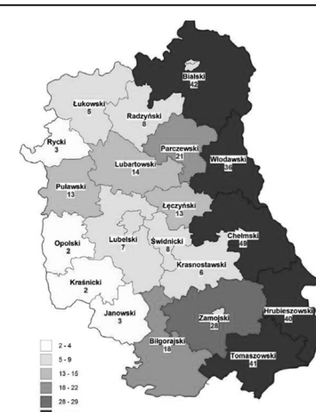
Obtained results indicate that even among smaller administrative units (counties, districts) there is quite a large variability of the technical potential for biogas production. The proposed method took into account all the circumstances affecting the theoretical and technical potential for agricultural biogas. The obtained results comprehensively reflect diverse opportunities for biogas production on a regional level.

3.3. Economic potential of the case study region

3.3.1. Scenario building

A scenario building method based on driving forces was used to evaluate the economic potential [12]. A scenario storyline was formulated, emerging from the basic policy question (a primary driving force): "Will the domestic RES policy give sufficient incentive for the RES development on a national level?", a negative answer leads to a negative future (SCENARIO S0), and to the discontinuation of the scenario building process. A positive answer leads to another question (a driving force 1): "Will the additional regional support be provided?", a negative answer leads to the SCENARIO 1, EASY FEEDSTOCK; a negative answer leads to the next question (a driving force 2): "Will the support be provided to all actors?". The answer: "The support will be provided only to big players" leads to the SCENARIO 2: EASY INTEGRATION. A positive answer leads to a more detailed question (a driving force 3): "Will intangible assets such as clustering activities, educational and consultancy measures for farmers be provided?", a negative answer leads to the SCENARIO 3: ENGAGEMENT OF SMALL FARMS. A positive answer to the last question leads to the extremely

Table 9
The input data for the evaluation of the feedstock potential for large feedstock suppliers.

Industrial organic waste producers	Animal waste (slurry, manure)	Energy crops
 × food industry ● large breeders		
Amount of agrifood waste producers	Livestock unit per 100 ha for farms >100 ha	Number of farms with acreage for farms >100 ha

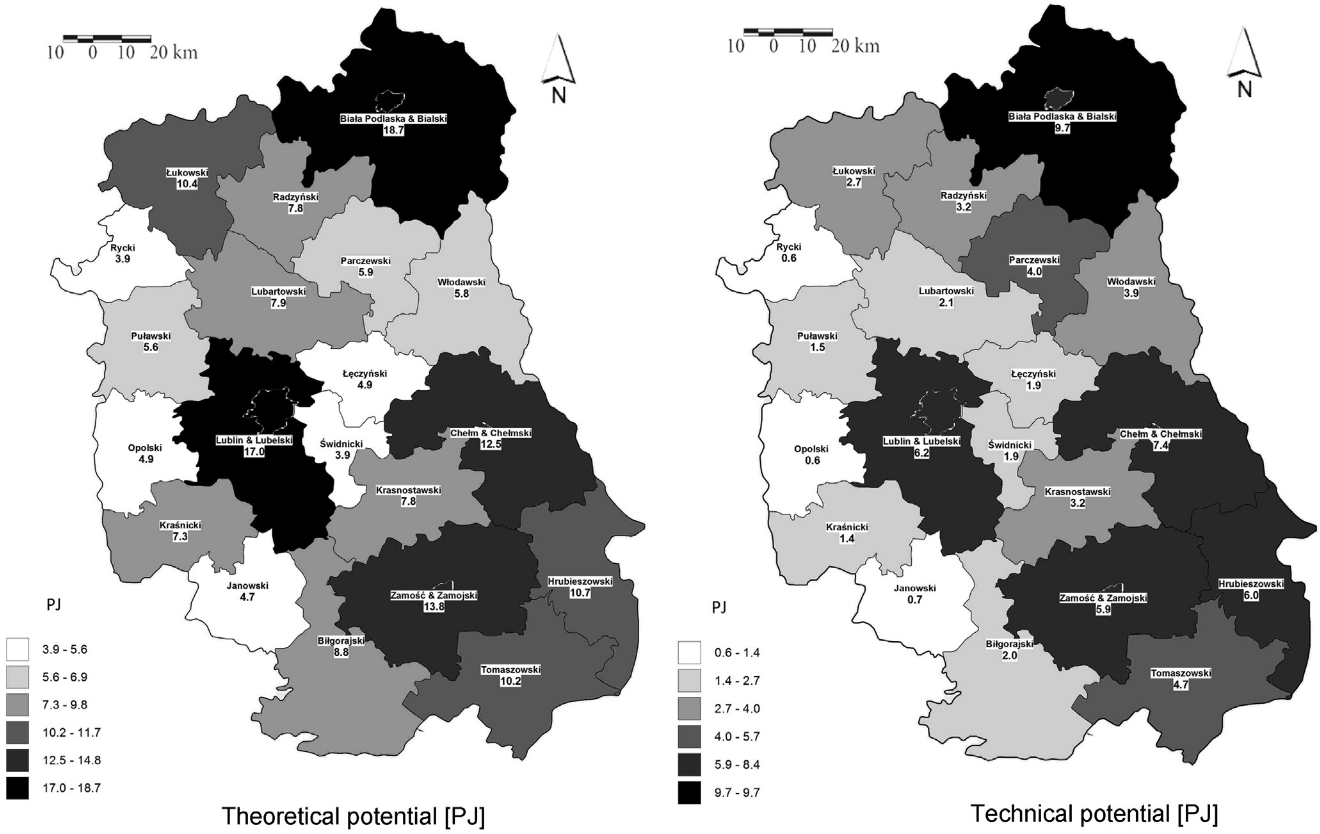


Fig. 1. The theoretical and technical potentials for agricultural biogas plants in the districts of the Lubelskie Province.

Table 10
Results of the technical potential calculations.

Technical potential	
Primary energy contained in biogas	70 PJ
Installed capacities	800 MW_{el}
% of share in the final electricity consumption	> 100% net exporter of electricity
Required area for energy crops	400,000 ha
% of UAA in good practice	29%
Farmers involved	
20–50 ha	8000
50–100 ha	1000
> 100 ha	400

positive future, *i.e.* SCENARIO 4: CONSOLIDATED ACTIONS. The scenario story line is presented in [71,72] Figs. 2 and 3.

The parametric assumptions for each scenario are entered to a dedicated Excel sheet stimulation tool, where scenario variables are interlinked in order to produce results. The results of the calculations, together with a narrative for each of the 4 scenarios are presented below (Tables 11).

For the S1 an average domestic emission indicators for the power sector were assumed at 0.781 gCO_2/kWh [65]. For the calculation of the ecological added value a dropping trend in specific CO_2 emissions was assumed due to decarbonisation of the domestic energy mix. In the mid/long term perspectives, S3–S4 assumptions are in line with the Poland's Energy Policy 2030, which assumes the achievement of less than 0.70 gCO_2/kWh in the year 2030 [73]. In order to calculate specific net emission reductions specific emissions from the biogas production should be deducted from specific power sector emissions [36]. Thus for the S1 the emission reductions for the regional added value calculated will amount to $0.781-0.290=0.491$ gCO_2/kWh.

For the calculation of the regional economic added value it was assumed that the investment costs for new capacities will stay at the level of 5 MEUR/MW_{el} for smaller and 3.8 MEUR/MW_{el} for bigger plants. The energy crop yields were assumed at 45 t/ha with the production costs 90 PLN/t (22.5 EUR/t) [22,71]. The electricity prices for the calculation of electricity fees staying in the region were assumed at 0.3 PLN/kWh *i.e* 7 cEUR/kWh (without the distribution fee). The prognoses for inflation are out of scope of this analysis, thus, the results are presented in EUR_{2013} monetary values.

3.3.2. *Scenario outcomes*

Scenarios should be described not only by numbers, a storyline with envisioned future developments reflecting inter linkages between scenarios assumptions and outcomes should be formulated. Such ways of presentation will be interesting in particular for the policy makers, who in real life are the final users of the scenario outcomes. In each of the scenarios energy crops play a crucial role as a substrate base for biogas. However, for sustainability reasons 2 criteria are always kept: energy crops do not take more than 10% of the arable land, and the mass inputs to agricultural biogas plants do not exceed 60% (90% in energy terms).

3.3.2.1. Easy feedstock scenario – S1. Policy implications: the S1 can be considered as a short term available potential to 2020. The targets assume that energy crops will be delivered from *c.* 10,000 ha, engaging some 30 bigger farms. The S1 assumes that the current level of support on the national level for RES/agricultural biogas will be continued. Assumed short term

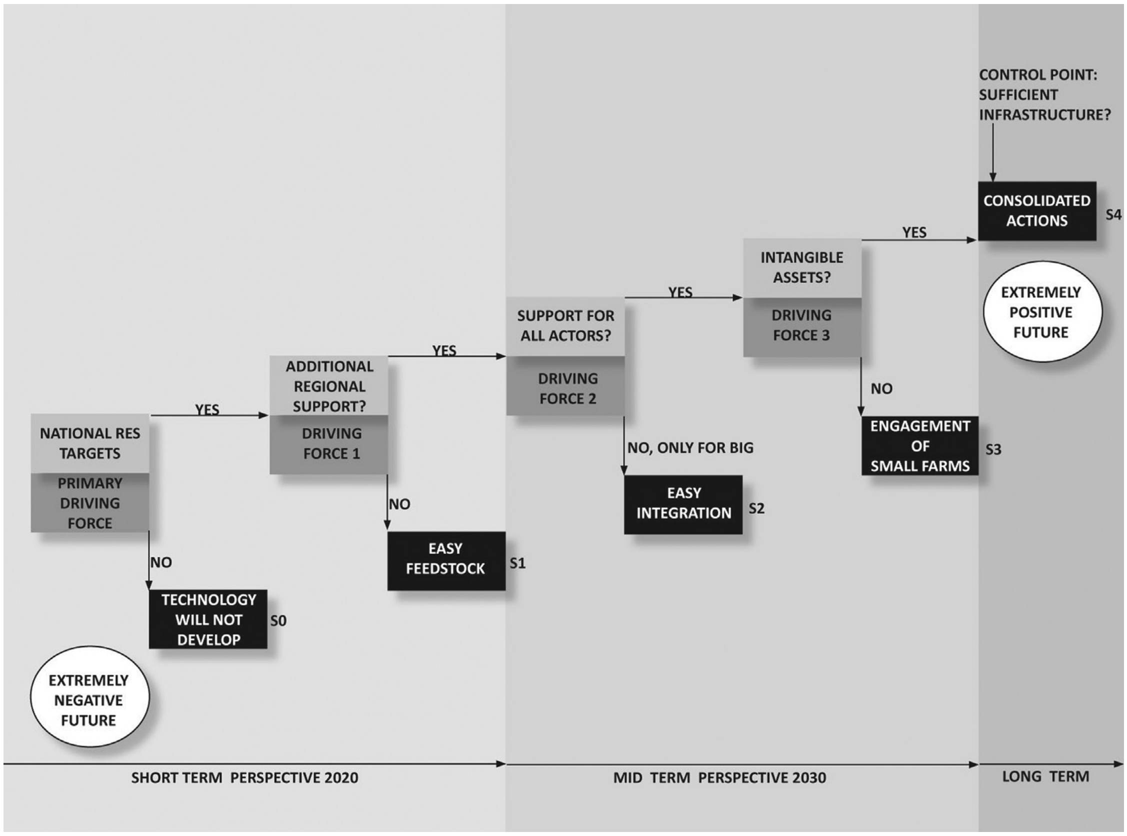


Fig. 2. Scenarios' storyline for the economic potential calculation.

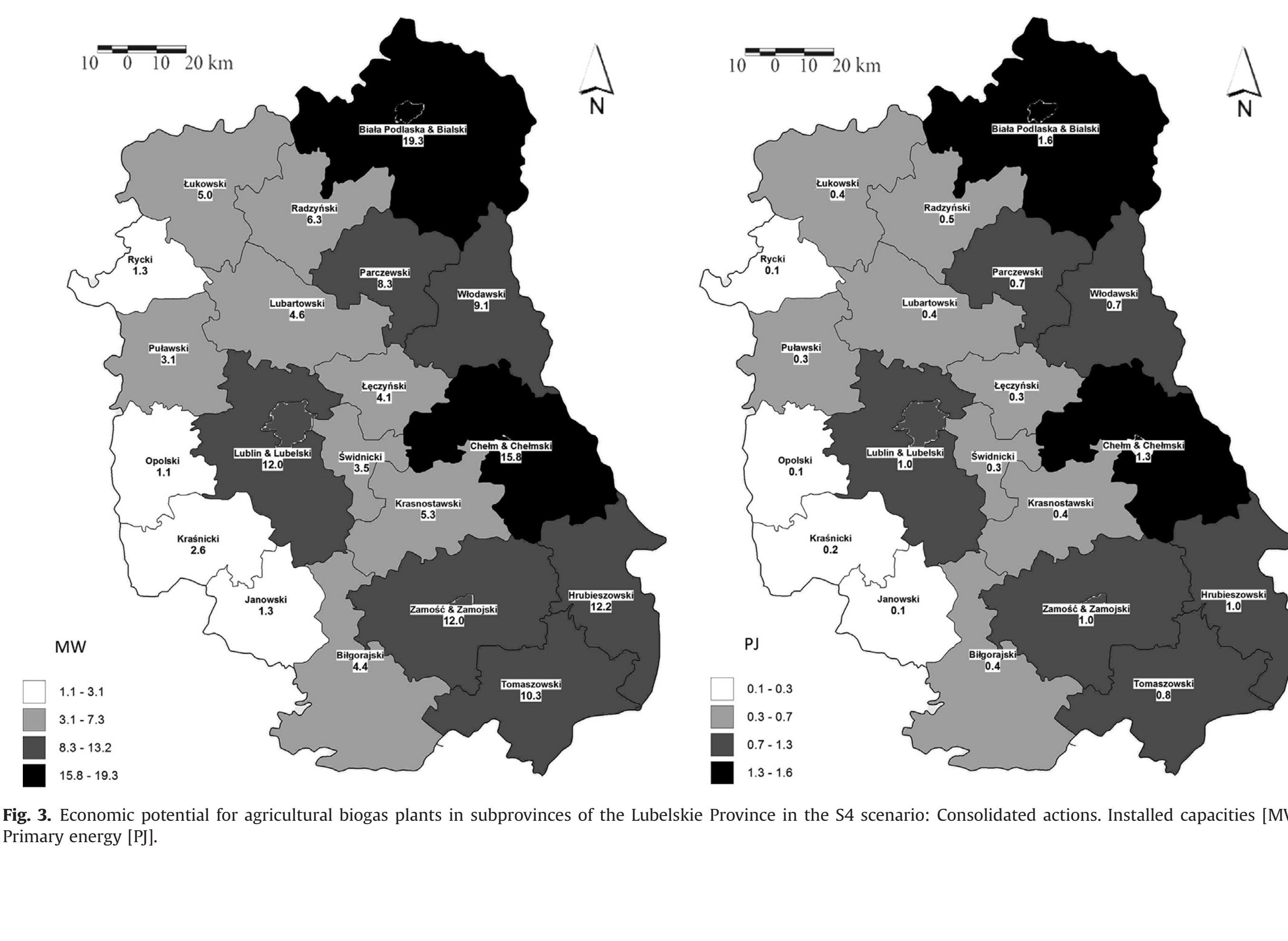


Fig. 3. Economic potential for agricultural biogas plants in subprovinces of the Lubelskie Province in the S4 scenario: Consolidated actions. Installed capacities [MW_{el}], Primary energy [PJ].

Table 11
Scenarios' assumptions.

Scenario name	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Easy feedstock	Easy integration	Engaging small farms	Consolidated actions
Time horizon	2020	2025	2030	2035
Farms' acreage	100 ha	50 ha	20 ha	20 ha
Interest in the energy crop production				
20–50 ha	0	0	5%	10%
50–100 ha	0	10%	15%	20%
> 100 ha	10%	15%	20%	25%
Fraction of disposable animal excrements	30%	40%	50%	60%
Fraction of disposable agrifood industry waste	50%	60%	60%	60%
Added value				
Power sector CO_2 emissions reduction (gross) coefficient gCO_2/kWh	0.781	0.70	0.65	0.60
Net emission reduction coefficient gCO_2/kWh	0.491	0.41	0.36	0.31

targets can be realised practically with no additional effort on a regional level, national incentives will be sufficient to stimulate the biogas market development. Installed biogas plants are likely to be based on a market sound technology *i.e.* CHP.

Results: in the scenario (S1) the substrate market potential expressed in installed power capacities amounts to 25 MW_{el} and is easily reached by 2020 (4% share in the final regional electricity consumption). The number of plants will raise to *c.* 15 large plants (waste potential from food industry will be almost entirely used up), and *c.* 25 medium sized. Small biogas plants will not develop under this scenario due to insufficient support from the national legislation. The area dedicated for energy crops is 10,000 ha; however, the requirements for land for fertilisation with digestate amount to 25,000 ha.

Regional added value: an additional part-time employment for *c.* 370 people in harvesting energy crops (for 2 months/a) and *c.* 100 jobs for O&M are expected (a few hours/d per each plant). The required area of energy crops is about 10,000 ha, which makes less than 1% of the share in arable land and calls for the involvement of *c.* 30 farms above 100 ha acreage. The cumulated carbon dioxide emissions reduction from electricity generation to 2020 will amount to 0.7 $MtCO_2$ and the annual regional turnover to 36 MEUR/a.

3.3.2.2. *Easy integration scenario – S2. Policy implications*: S2 can be considered as a mid-term available potential to 2025. The targets assumed in the S2 are to deliver energy crops from *c.* 20,000 ha and to engage some 150 bigger farms above 50 ha. In the short and midterm perspective social acceptance problems should be resolved if the number of biogas plants is to increase. Thus, educational programmes both for farmers willing to participate in the local biogas market as well as for citizens are recommended as the top priority action in this scenario.

Results: the scenario S2 assumes the intensification of energy crops production (such as maize) as an input material but only among bigger players (farms above 50 ha). The condition for achieving *c.* 50 MW_{el} of installed capacities (7% share in final electricity consumption) is to involve 10–20% farms in the production of dedicated energy crops (in total about 150 farms). The expected number of plants amounts to *c.* 25 large plants > 1 MW_{el}, 50 medium sized plants 150–500 kW_{el} - no small installations are expected. The area required for energy crops is 20,000 ha, however, the requirements for land for fertilisation with the digestate amounts to 50,000 ha.

Regional added value: the additional part-time employment for *c.* 800 people in the harvesting of energy crops (for 2 months/a) and *c.* 200 jobs for O&M are expected (a few hours/d per each plant). The required area of energy crops is about 20,000 ha, which makes more than 1.5 % of the share in arable land. The cumulated carbon dioxide emissions reduction from the electricity generation to 2025 will amount to 2.0 $MtCO_2$ and the annual regional turnover by 2025 to 64 MEUR/a.

3.3.2.3. *Engaging small farms scenario – S3. Policy implications*: S3 can be considered as a long-term available potential to 2030. The targets assumed in the S3 are to deliver energy crops from *c.* 40,000 ha and to engage some 550 farms above 20 ha. The realisation of such ambitious targets will require setting up investment support schemes for smaller farmers, willing to engage in the production of feedstock. Due to the dispersed character of the agrarian structure, it is recommended to support consolidation actions (joint production of feedstock and biogas by farmers' cooperatives). Production of biogas it is not an easy task; therefore, technical educational programmes dedicated for farmers should be offered.

Results: S3 assumes the intensification of energy crops production (such as maize) as an input material for agricultural biogas among farms above 20 ha. The condition for achieving *c.* 100 MW_{el} of installed capacities (11% share in the final electricity consumption) is to additionally involve 5% of smaller farms in the production of dedicated energy crops (in total about 550 farms and 40,000 ha). Expected are *c.* 30 large plants > 1 MW_{el}, 80 medium sized plants 500–1000 kW_{el} and 200 smaller plants 150–500 kW_{el}. The required area for energy crops is about 40,000 ha, which makes more than 3% of the share in arable land, and for spreading of the digestate is 100,000 ha.

Regional added value: the additional part-time employment for *c.* 1500 people in harvesting energy crops (for 2 months/a) and *c.* 900 jobs for O&M (a few hours/d per each plant) are expected. The cumulated carbon dioxide emissions reduction from the electricity generation to 2030 will amount to 4.9 $MtCO_2$ and the annual regional turnover to 120 MEUR/a.

3.3.2.4. *Consolidated actions scenario – S4. Policy implications*: S4 can be considered as a long-term available potential to 2035. The scenario S4 assumes that the uninterrupted integrated RES regional policy will bring its long term fruits. A dynamic development of RES will be facilitated by the necessary organisational and a technical infrastructure. The targets assumed in the S4 are to deliver energy crops from *c.* 60,000 ha and to engage some 1,000 farms above 20 ha in either feedstock or biogas production. It is expected to be a logistic and organisational challenge and will require activities aimed at the consolidation, education and training of farmers. The scenario dwells on the strengthening of the social network. The regional authorities should make an effort to support intangible assets and the cooperation between farmers, scientists, NGOs and municipalities; the best option for such cooperation is to support clustering activities and the local

entrepreneurship. The most important task will be to facilitate the horizontal consolidation of farms for a joint production of biogas and energy crops. In this scenario biogas plants, with the possibility to store energy, start to play a role as balancing medium in the regional power system (a demand side management option for the production of energy from other intermittent RES such as wind and PV). In this scenario technologies, other than cogeneration, start to gain a momentum (a few projects producing biomethane for gas grids and for transportation).

Results: the total installed capacities will reach 140 MW_{el} will entail the involvement of some 1,000 of farms in the production of dedicated energy crops, with almost 5% of the arable land. Expected are *c.* 40 large plants >1 MW_{el}, 100 medium sized plants 500–1000 kW_{el} and 300 smaller plants 150–500 kW_{el}. The area dedicated for energy crops is *c.* 60,000 ha, however, the land requirements for the fertilisation with the digestate amounts to 145,000 ha.

Regional added value: the additional part-time employment for *c.* 2300 people in harvesting energy crops (for 2 months/a) and *c.* 1300 jobs for O&M are expected (a few hours/d per each plant). The cumulated carbon dioxide emissions reduction from electricity generation to 2035 will amount to 7.7 $MtCO_2$ and the annual regional turnover in this year to 165 MEUR/a. In this scenario the biggest economic added value is created by the energy crop production (Table 12).

An important issue in the operation of biogas plants is the possibility to utilise digestate as a fertiliser. The analyzes show that the area required for the utilisation of the digestate is more than twice larger than the area dedicated for energy crops cultivation. Therefore, a part of the digestate will have to be utilised in food crops fields. The digestate can also be used in specialized farms with a dominant crop production. Due to the lack of natural fertilizers (manure) and intensive crop production, they have problems maintaining a positive balance of soil organic matter. The use of digestate can limit this problem and have a positive impact on the quality of soil and crop yields. It should be noted that the use of the digestate for fertilising may also be economically beneficial. Mineral fertilizers are now an important and significant part of the cost of crop production; therefore, replacing them with the digestate should improve the energy crops' economy.

Some problems with the management of the digestate may occur in areas characterised with a high concentration of livestock production, where natural fertilizers are abundant. Because the dosage of the *N*-total in any fertiliser per unit of land has been limited, in some areas it may happen that a part of the digestate will have to be transported over long distances. This solution provides a number of technical and logistical problems. However, the obtained results indicate that in the case Lubelskie Province there should not be major difficulties with the local management and uptake of the produced digestate.

3.3.3. Sensitivity analysis

The sensitivity analyses were performed, *ceteris paribus*, for the crucial scenario parameters, listed in Table 11. The most important parameter is the farmers' willingness to engage in energy crops production; followed by the fraction of animal and agrifood waste, which can be obtained as input material to agricultural biogas plants. The analyses show that the interest indicator in two groups of farm sizes 20–50 ha and above 100 ha are the most sensitive parameters. In the S4 increasing the interest of farms in the production of dedicated energy crops in smaller farms from 10% to 20% can lead to almost 140 MW_{el} of the total regional biogas installed capacities. The sensitivity analysis also showed a very limited impact of the agrifood industry waste as input material [71] (Figs. 4 and 5).

Table 12
The summary of the scenarios' approximated outcomes.

Scenario name	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Time horizon	**Easy feedstock** 2020	**Easy integration** 2025	**Engaging small farms** 2030	**Consolidated actions** 2035
Energy				
Primary energy contained in the biogas	2 PJ	4 PJ	8 PJ	12 PJ
Installed capacities	25 MW_{el}	50 MW_{el}	100 MW_{el}	140 MW_{el}
Electricity production	190 GWh	410 GWh	800 GWh	1130 GWh
Number of biogas plants	40	75	310	440
With capacity shares:				
Large >1 MW_{el}	50%	50%	30%	30%
Medium 500–1000 kW_{el}	50%	50%	40%	40%
Small 150-500 kW_{el}	0	0	30%	30%
Share in the final electricity consumption	4%	7%	11%	15%
Agriculture				
Required area for energy crops	10,000 ha	20,000 ha	40,000 ha	60,000 ha
% of arable land area in good practice	<1%	1.5%	3%	4.5%
Farms involved				
20–50 ha	0	0	350	700
50–100 ha	0	100	150	200
>100 ha	30	50	50	80
Area required for fertilisation with digestate	25,000 ha	50,000 ha	100,000 ha	145,000 ha
Regional added value				
Employment (FTE)				
Seasonal employment(energy crops)	370	800	1500	2300
O&M	100	200	900	1300
Regional annual turnover (MEUR)	in 2020: 36 MEUR/a	in 2025: 64 MEUR/a	in 2030: 120 MEUR/a	in 2035: 165 MEUR/a
New investments (annual)	13	15	24	27
Electricity fees staying in the region (annual)	13	27	54	76
Energy crop production (annual)	10	22	42	62
Net CO_2 emission reduction $MtCO_2$				
By electricity generation (cumulated)	0.7	2.0	4.9	7.7
By electricity generation (annual)	0.1	0.2	0.3	0.4

3.4. Policy implications

The contemporary common approach to fuel based RES planning has been to calculate the technical potential and evaluate the biomass feedstock availability, without elaborative studies of other assets, important for the policy formulation. However, the very integration of the resource potential with other assets is considered to be pillars of the future RES diffusion in a given region. The scenarios' story line and assumed targets led to the formulation of policy implications, which are summarised below.

The below framework recommendations are suggested for the integration into official policy documents of the Lubelskie Province. Policies should include clear targets within chosen time horizons as well as designate authorities responsible for their implementation, monitoring and update. The below formulated list of recommendations was formulated after a public consultation meeting, involving local stakeholders: regional authorities, municipalities, framers' associations, agrifood industry representatives, biogas plants developers and citizens [71]. The below list of assumptions for a policy implementation is not complete, but indicates the most important points to be accounted for.

Policy implementation: assumed policy targets should be concrete in numbers (not vague and general), have a clear time horizon; be accompanied with a set of policy-push measures. Additionally there should be a political declaration for their endorsement by the regional authorities. Regional policies such as energy, agricultural and social should be integrated horizontally for example *via* a spatial planning policy.

Technical assistance for municipalities: municipalities are not eager to make an effort to integrate different RES policies due to costs, time, lack of data and expertise. Therefore, they should be advised, at least in the initial stage, on how to integrate plans for extension of new, planned energy infrastructures into local policy documents (*e.g.* spatial and/or energy master plans), as well as into the investment process. Such technical and organisational assistance should be provided by the regional authorities.

Information and education: the regional authorities should continually initiate and support local expertise, thematic publications, trainings, workshops and increase public acceptance for agricultural biogas plants. Both citizens, as well as municipal authorities and investors/developers should be approached to learn how to co-operate and resolve conflicting situations. The construction of biogas plants should be perceived positively by the authorities and the local population in order to create acceptance and avoid escalation of protests against investments of infrastructural origin.

Investment support: the regional RES investment support should have clear targets and budgets. The purpose of planning is that the financial support is targeted at investments with the greatest economic potential. The development strategy of dispersed generation (incl. biogas) should actively involve local authorities. The first biogas installations erected with the public support should be converted into open-access vocational training, and educational units.

Consolidation of actors: due to economic reasons it is recommended that farmers work together in order to jointly produce feedstock and energy. The horizontal consolidation and co-operation of farmers will

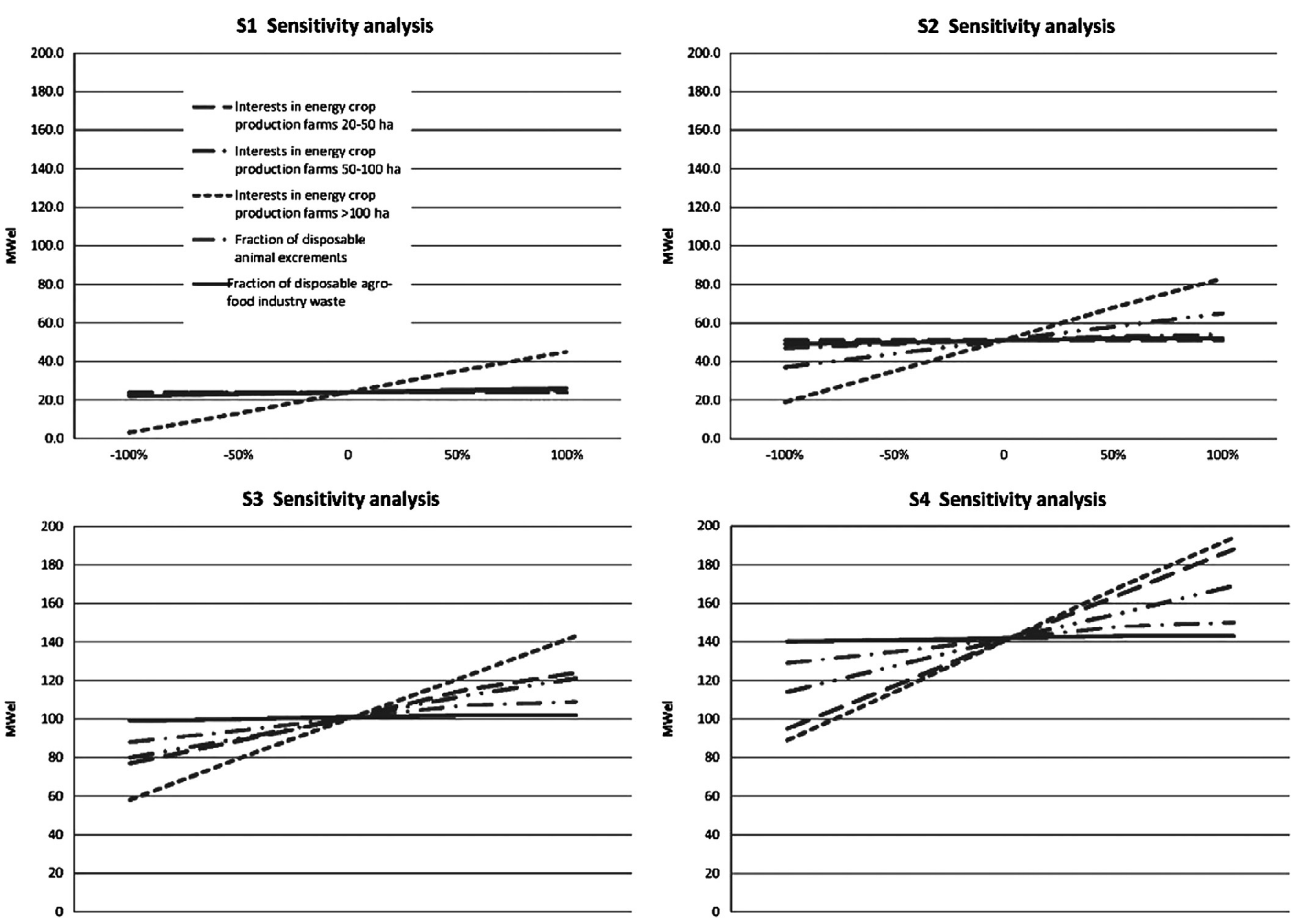


Fig. 4. Scenarios' sensitivity analyses.

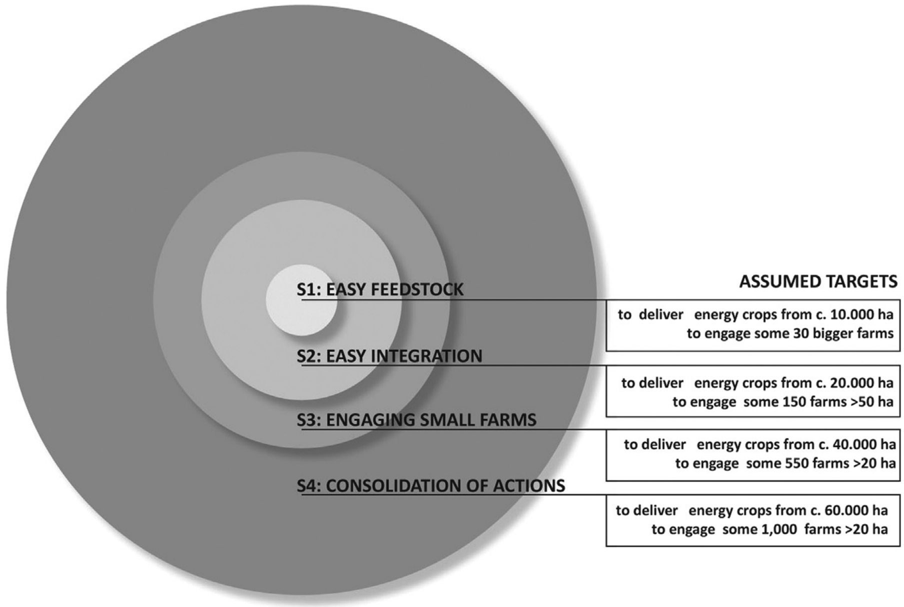


Fig. 5. Targets assumed for the scenarios.

Table 13
The comparison of the S4 long term scenario outcomes to the status quo situation in a biogas mature region.

Time horizon	Lower Saxony	Lubelskie province
	Status quo Over 30 years of support	**Scenario 4** 2035
General		
Area	4.8 Mha	2.5 Mha
Agricultural area	2.6 Mha (80% of land)	1.5 Mha
Population	8 million	2.2 million
Energy		
Installed capacities	783 MW_{el}	150 MW_{el}
Electricity production from biogas	5800 GWh	1130 GWh
Number of biogas plants, with capacity shares:	1480	450
Large $>$ 1 MW_{el}	20%	30%
Medium 500–1000 kW_{el}	22%	40%
Small 150–500 kW_{el}	57%	30%
$<$ 150 kW_{el}	1%	0%
Share in the final electricity consumption	10%	15%
Agriculture		
Required area for energy crops	240,000 ha	60,000 ha
Mass share of energy crops in biogas substrates	54%	60%
Share of energy crops in the RES electricity production	79%	89%
% of arable land area	2–20% av. 6.7%	1.2–8.8% av. 5%
Farmers involved	3000	1000
Regional added value		
Employment (FTE)	1500 direct, 5000 indirect	1600 FTE (seasonal converted into FTE)
Net regional annual turnover		
New investments (annual)	2500/10 years (250 MEUR/a)	165 MEUR/a

not happen without external organisational support, thus, the regional authorities should facilitate planning, organisation and financing of the first thematic co-operatives in rural areas. The process of horizontal consolidation of smaller farms should be aimed at co-operatives of biogas and energy crops producers. The region should take an advantage of the existing local organisational infrastructure such as regional agricultural advisory centres. Another direction could be to strengthen the creation and activity of a thematic cluster consisting of suppliers, customers and associated industries, but also added value-chain actors such as universities, research institutions, local governments, industry associations, financial institutions and intermediary organisations of science and technology.

3.5. Replication potential

In order to evaluate the reliability of the analysis, the results for a given region can be benchmarked against another one, which has been developing agricultural biogas plants with success for over 30 years. The status quo situation in the Lower Saxony, Germany is compared to the outcomes of the S4 long term

scenario for the Lubelskie Province. Germany's biogas market is the largest in Europe, whereas, Lower Saxony boasts over 20% of the domestic production. The local farmers as well as endorsed policy push actions stimulated a dynamic growth of the sector (in 2012: 1480 plants with 783 MW_{el}, additionally 21 biomethane installations feeding gas to the natural gas grid and a few biogas fuelling stations for transportation). The biogas support scheme led to the engagement of 3000 farmers, 2.5 billion EUR investments in rural areas since 2002 and 1500 direct (and 5000 additional indirect) work places. Until 2020 the biogas capacity is projected to further grow to 900 MW_{el} [69,74] (Table 13).

The area of Lower Saxony is 2 times and the population 3.6 times bigger than in the Lubelskie Province. However, the achievable targets for the Lubelskie Province in the next 20–25 years are 5 times smaller due to economic and organisational constraints. Lower Saxony is one of the most developed, industrial regions in Germany with a well developed network of intangible assets (science, research, organisation); whereas, the Lubelskie Province remains one of the poorest, agricultural EU regions looking for its own specialisation [72].

Prior to this study a similar methodology was partly replicated for the evaluation of agricultural biogas potentials in other regions in Poland (16 NUTS 2 regions, called voivodships). In the regional study for the Ministry of the Regional Development (MRD) [75] a similar methodology was applied; however, with much restricted development criteria, as a result the technical potential for the Lubelskie Province is smaller compared to this study. However, in the case of the economic potential, although calculated only for the short-term: 3 PJ (42 MW_{el}), it resembles the results of this study 2 PJ (25 MW_{el}) in the S1 and 4 PJ (50 MW_{el}) in the S2. The economic potential for the medium and long term was not calculated in the MRD analysis because a longer time horizon (after 2020) was not of interest to the contractor: the results were supposed to be used as an indication for financing of RES in the new EU 2014–2020 perspective.

Thus, the usability of the presented methodology depends on the context and the purpose of producing final results. The authorities of the Lubelskie Province were interested in a 20–25 years time horizon in order to formulate a long term regional development plan, on the other hand the Polish government was interested in short term recommendations for the new EU funds. If applied for a long-term, the policy makers should remember that there is a long way from the design/initiation of policies to achieving the assumed targets: the timeframe of the analysis should be considered with due care. In the medium and long term the dynamic development occurs with some time lapse (5–10 years), it is preceded by planning, controversial debates, a stakeholders' involvement and demonstration projects. The policy realisation calls for a political involvement that extends beyond a short-term election period.

Regional perspectives have become increasingly important to realise the national and global green energy policies. However, there is no ready receipt for the achievement of such goals, each region should make an effort to look for specialisations, enabling them to become competitive. Assuming that the data availability is comparable; this methodology could be implemented in many other regions. The elaborated methodology can find application also on other administrative levels: higher (national) and lower (subregional) NUTS 1–3, LAU 4–5. The recommendation for other regions is that not only substrate based theoretical and technical potentials should be in focus of such studies. For the formulation of policies the market potential with the consideration of short, medium and long term perspectives is crucial. Future market frameworks are to be anticipated and creatively incited in order to evaluate infrastructural investment needs and to create a regional added value (employment, turnover and environmental benefits).

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